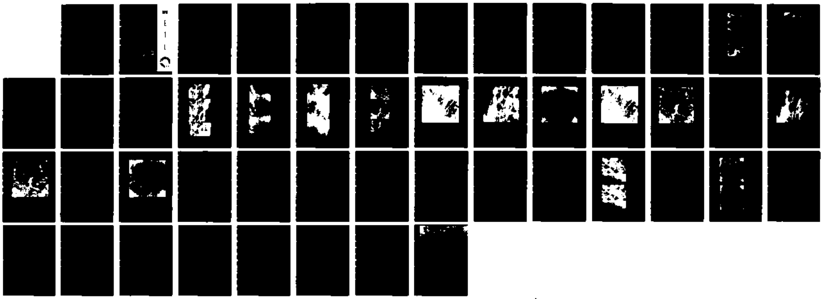
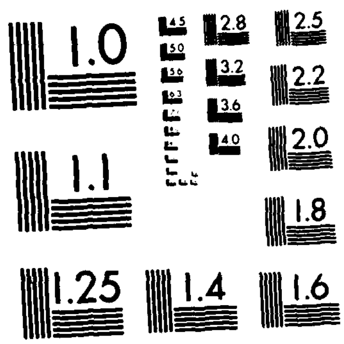
AD-A134 965 THE CLASSIFICATIONS OF METAMORPHIC ROCKS AND THEIR APPLICATIONS TO AIR PHOTO INTERPRETATION PROCEDURES(U) ARMY ENGINEER TOPOGRAPHIC LABS FORT BELVOIR VA J EHLEN SEP 83 ETL-0341 1/1

UNCLASSIFIED F/G 8/7 NL




1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0

(6)

ETL-0341

AD-A134 965

The classifications of metamorphic rocks and their applications to air photo interpretation procedures

Judy Ehlen

September 1983

U.S. ARMY CORPS OF ENGINEERS
ENGINEER TOPOGRAPHIC LABORATORIES
FORT BELVOIR, VIRGINIA 22060

83 11 28 200

E
T
L

U.S. ARMY ENGINEER TOPOGRAPHIC LABORATORIES
ETL

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ETL-0341	2. GOVT ACCESSION NO. AD-A134	3. RECIPIENT'S CATALOG NUMBER 965
4. TITLE (and Subtitle) THE CLASSIFICATIONS OF METAMORPHIC ROCKS AND THEIR APPLICATIONS TO AIR PHOTO INTERPRETATION PROCEDURES		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Judy Ehlen		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Engineer Topographic Laboratories Fort Belvoir, Virginia 22060		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 4A161102B52C, C, 0010
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Engineer Topographic Laboratories Fort Belvoir, Virginia 22060		12. REPORT DATE September 1983
		13. NUMBER OF PAGES 43
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Metamorphic Rocks
Photo Interpretation
Remote Sensing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Although there are stated Army needs for rock-type information, there are as yet few reliable procedures for obtaining much of this information, particularly for metamorphic rocks, via remote sensing. The three common classifications of metamorphic rocks, i.e. textural, facies, and formational, were evaluated in terms of their usefulness in predicting metamorphic rock types using air photo interpretation procedures. Areas in the northeastern United States containing a wide range of metamorphic rocks were selected as test areas. Predictions of rock type were verified by field reconnaissance and comparison to geologic maps. Although none of the three classifications

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. Abstract (Continued)

were found adequate for use on air photos, the results of this study indicate that the potential for successfully predicting metamorphic rock types by air photo interpretation procedures exists. The textural classification was found most useful, primarily because criteria for identifying metamorphic rocks on air photos using this classification were developed previously. Although using the facies classification has potential, it is unlikely that it can be used routinely in conjunction with air photo interpretation procedures because of the high degree of skill required to identify metamorphic facies. The formational classification was found to be useful because it identifies metamorphic rocks by mapping unit, but it does not provide a mechanism for naming the rock units.

PREFACE

This study was conducted under DA Project 4A161102B52C, Task C, Work Unit 0010, "Indicators of Terrain Conditions."

I wish to thank Dr. E--an Zen, U.S. Geological Survey, Reston, Virginia, for providing the idea for this study, for lending me his air photos of the Vermont and Massachusetts areas and his thin sections of the Vermont area, for his support and guidance in the field, and for his encouragement throughout the project; Ms. Jean Benson, Computer Sciences Laboratory, ETL, for introducing me to the West Point, New York, area and for her assistance in the field and laboratory; and Dr. Nicholas M. Ratcliffe, U.S. Geological Survey, Reston, Virginia, for providing references and unpublished data about the West Point, New York, area in addition to giving me copies of his unpublished geologic maps of the Peekskill, Oscawana Lake, and Mohegan Lake quadrangles (West Point, New York, area). I would also like to thank Cedric I. Key and the personnel of the Publications Support Team, Terrain Analysis Center, ETL, for their assistance in planning and preparing the illustrations for this report.

The study was done during the period October 1981 to October 1982 under the supervision of Dr. J.N. Rinker, Team Leader, Center for Remote Sensing; and M. Crowell, Jr., Director, Research Institute.

COL Edwin K. Wintz, CE, was Commander and Director and Mr. Robert P. Macchia was Technical Director of the Engineer Topographic Laboratories during the study period.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

TABLES

THE CLASSIFICATIONS OF METAMORPHIC ROCKS AND THEIR APPLICATIONS TO AIR PHOTO INTERPRETATION PROCEDURES

INTRODUCTION

Various digital terrain data bases (DLMS, PTADB, TTADB, etc.) require different levels of rock type information. In order to provide such information via air photo interpretation procedures, it is necessary to discover and evaluate pattern element indicators of the rock systems, e.g. igneous, sedimentary, and metamorphic, as well as of the specific rock types within these systems. Furthermore, such indicators are needed before knowledge-based systems can be developed as part of interactive analysis systems for identifying rock material on imagery. At present, identifying metamorphic rocks by air photo interpretation procedures is very difficult, and there are few, if any, reliable indicators for consistently separating metamorphic from igneous and sedimentary rocks, much less for identifying specific metamorphic rock types. This study is directed toward developing such indicators for metamorphic rocks.

Regionally metamorphosed rocks are classified and mapped in several ways: by texture, by facies or composition, and by formation. The textural classification is the method used by Belcher and others (1951), von Bandat (1962), and Way (1973) and forms the basis for the published criteria for identifying metamorphic rocks on air photos (Ehlen, 1983). In this method, the rocks are classified by their physical appearance in hand specimen or outcrop, e.g. slatey, schistose, gneissic. Rocks with slatey cleavage or foliation are formed of very small, tabular mineral grains and split into thin, even slabs (figure 1). Roofing slates are an example. Schistose rocks contain mineral grains that are large enough to be recognized in hand specimen, are well foliated, and cleave into thin flakes (figure 2). Schistose rocks often contain large mineral grains called porphyroblasts. Gneissic rocks are generally coarse grained and are formed of alternating bands of light and dark minerals arranged parallel to each other (figure 3). Gneissic rocks commonly exhibit a coarse-grained planar fabric and may also be lenticular in texture. Typical textural rocks names are garnet schist and biotite gneiss.

A second way to classify metamorphic rocks is by composition (mineral assemblages) or facies. Each facies represents a section of a pressure/temperature continuum in which certain specified mineral associations can occur; exactly which minerals comprise a stable assemblage depends on the combination of temperature, pressure, and original composition. Use of this classification relies on one's ability to identify critical minerals in a rock and normally requires the use of microscopic and other laboratory methods. The name given to a rock includes the names of the major stable minerals and the facies to which that assemblage belongs, such as orthopyroxene-plagioclase granulite.

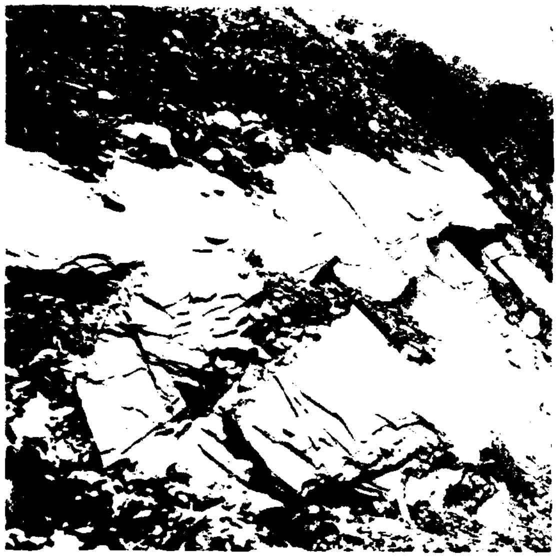


FIGURE 1. Characteristic appearance of a slate outcrop, west-central Vermont.

SOURCE: Photo by E-an Zen.

FIGURE 2. Characteristic appearance of a schist, north west Connecticut.

FIGURE 3. Gneissic banding near West Point, New York.

The third way to classify metamorphic rocks, by formational unit, is probably the most common on geologic maps (Zen and Hartshorn, 1966; Zen and Ratcliffe, 1971, for example). This method relies on precise boundary delineation, and naming or identifying the rock units is accomplished by using either the textural or facies classification. In addition, this approach involves recognizing the premetamorphic stratigraphic relationships between different rock types in that the premetamorphic lithologies, sedimentary characteristics, and/or fossils form the basis for mapping, regardless of changes in composition caused by metamorphism. In low- to medium-grade rocks, this can be relatively easy, but it becomes much more difficult with higher grade rocks because the greater the degree, or the amount, of metamorphism and deformation, the greater the degree of physical, chemical, and structural change and the more similar the rocks can become in appearance. Formational names, such as Walloomsac Formation, are used in addition to describing the rocks in terms of texture, major mineral components, or facies.

These are the three classification methods used by most geologists. All three have some disadvantages when used in conjunction with air photo interpretation procedures. All three, for instance, are hampered by the physical, chemical, and structural complexities of the metamorphic rocks themselves and by the generally limited knowledge about metamorphic phenomena.

Although the textural classification indicates relative grade (slatey-low; schistose-medium; gneissic-high), the textural rock names say little about the composition or origin of the rocks. The practice of adding the names of primary mineral components to the textural name, such as hornblende gneiss or kyanite schist, however, does provide some information about both present and original composition of the rock. Although the textural classification is relatively simple and is easy to use in the field, problems arise when this method is used in conjunction with air photo interpretation procedures. The use of this classification implies that foliation is apparant on air photos, but this is not usually the case. Allum (1960-61), for instance, indicates that linear patterns in metasedimentary terrains that could be interpreted as foliation on air photos are usually relict bedding. It is possible, however, that differences in foliation could produce differences in landform and drainage patterns that are discernible on air photos.

The facies classification is probably the most useful of the three because it is based on the lithology of the rocks as they are. It is not strictly based on composition, because rocks of the same original composition can occur in different facies or subfacies, depending on the degree of metamorphism. This classification, however, much more directly reflects composition than do the other two methods of classification. No work has as yet been done to relate air photo patterns and metamorphic facies, but because igneous and sedimentary rocks can be identified on air photos by composition (Ehlen, 1976, 1981, and unpublished data), it seems reasonable that distinctive photo patterns can be determined for each metamorphic facies and/or subfacies. A much greater knowledge of metamorphic petrology is required to verify rock type predictions using the facies classification than for either the textural classification or the formational approach, so the potential usefulness of this classification on air photos is, in practice, limited. Verification of facies or subfacies predictions can also be difficult because facies are rarely indicated on geologic maps and are usually described textually. Isograds, lines representing the points of appearance and disappearance of specified minerals, are occasionally shown on geologic maps, however; and although isograds are not strict representations of facies or subfacies, they usually provide the information required for facies or subfacies determinations.

Although the formational approach relies on precise boundary delineation and does not entail the naming of rock units, it is included here because it is the most commonly used method for mapping metamorphic rocks. There are problems, however, with using the formational approach to classify metamorphic rocks on air photos. Regional metamorphism is areal in extent; thus, one part of a sedimentary formation may have been metamorphosed while another part may remain in its original state. In addition, the degree of metamorphism can vary laterally across a formation as well as along the length of a formation. This could be particularly confusing from the air photo interpretation point of view. Nevertheless, there is no apparent reason, why this approach could not be used on air photos: it works quite well with sedimentary rocks (Ehlen, 1981). Each formational lithology or combination of lithologies should exhibit distinctive landform and drainage patterns. A problem could arise when the boundaries between different metamorphic grades (indicated on geologic maps by isograds) occur at an angle to formational boundaries. In such cases, similar rocks can occur in different formations, and the landform and drainage patterns would reflect the differences in existing, rather than premetamorphic, lithology. The photo interpreter would probably delineate areas of similar rock type rather than consistent formational units.

OBJECTIVE

The purpose of this study was to determine which, if any, of the systems of classifying metamorphic rocks can be used to identify metamorphic rocks on air photos. Consequently, all photo analyses and predictions of rock type were completed prior to field work, perusal of the literature, or comparison to the geologic maps for verification. Three areas in the northeastern United States were selected to evaluate these systems (figure 4). The first area, near Rutland, Vermont, consists of low-grade rocks, primarily slates and phyllites (figure 5). The second area, in southwestern Massachusetts, consists of similar rocks, but the phyllites are slightly higher in grade than in the Vermont area, and marbles are also present (figure 6). The third area, centered on West Point, New York, consists of high-grade rocks, primarily gneisses (figures 7 and 8). All three areas have undergone regional metamorphism. Continental glaciation has also affected each of the three areas; the glacial effects on topography are least significant in the West Point, New York, area.

PROCEDURES

The photos used in each study area are listed in table 1. One photo analysis was done in the Vermont area and one was done in the Massachusetts area. Two photo analyses were done in the West Point, New York, area; one at 1:120,000 scale and a second at 1:35,000 scale. Figure 9 shows the location of the 1:35,000 scale photos in relation to the 1:120,000 scale West Point, New York, study area. The photo analysis procedures used in this study are described in Frost and others (1951), Rinker and Frost (1981), and Rinker and Corl (1983). Each study area was evaluated on the air photos in terms of the pattern elements: landform, drainage-plan, drainage-cross section, photo tone, and photo texture; the pattern element descriptions for the photo mapping units in the Vermont and West Point, New York, areas are published in Ehlen (1983), and those for the Massachusetts area are shown in appendix A. The photo mapping units in each area are shown in figures 10, 11, 12, and 13.

TABLE 1. Photography used in the three study areas

Area	Type of Photography	Origin of Photography	Scale
Vermont	Panchromatic	ASCS, 1942 DCC-3-155, 156, 157	1:20,000
Massachusetts	Panchromatic	ASCS, 1952 DPM-3K-28, 29, 30	1:20,000
West Point, New York	Color infrared	NASA, 1973 9703, 9704, 9705	1:120,000
	Panchromatic	ASCS, 1974 174-191, 192, 193	1:35,000

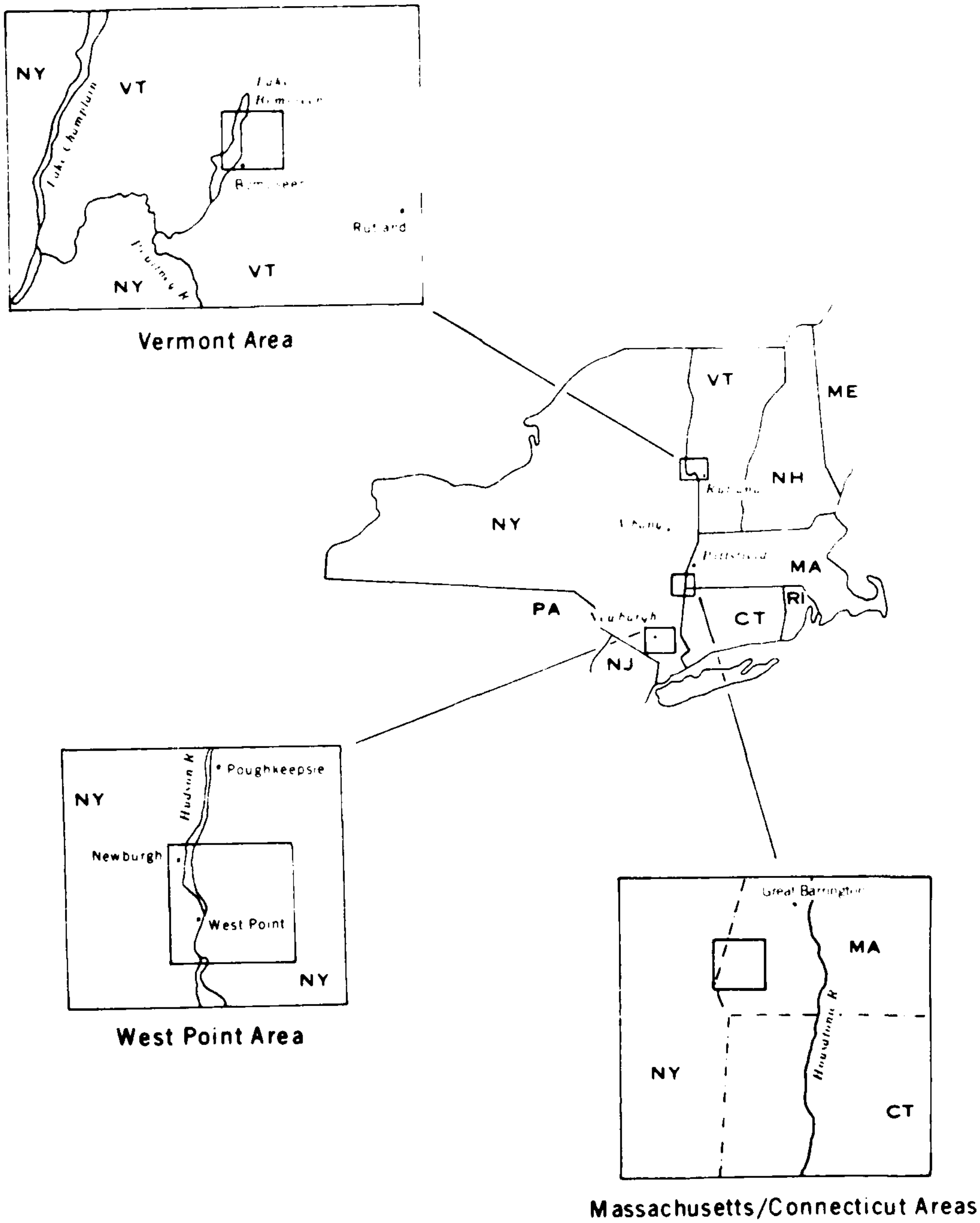


FIGURE 4. Index map showing the locations of the three study areas.

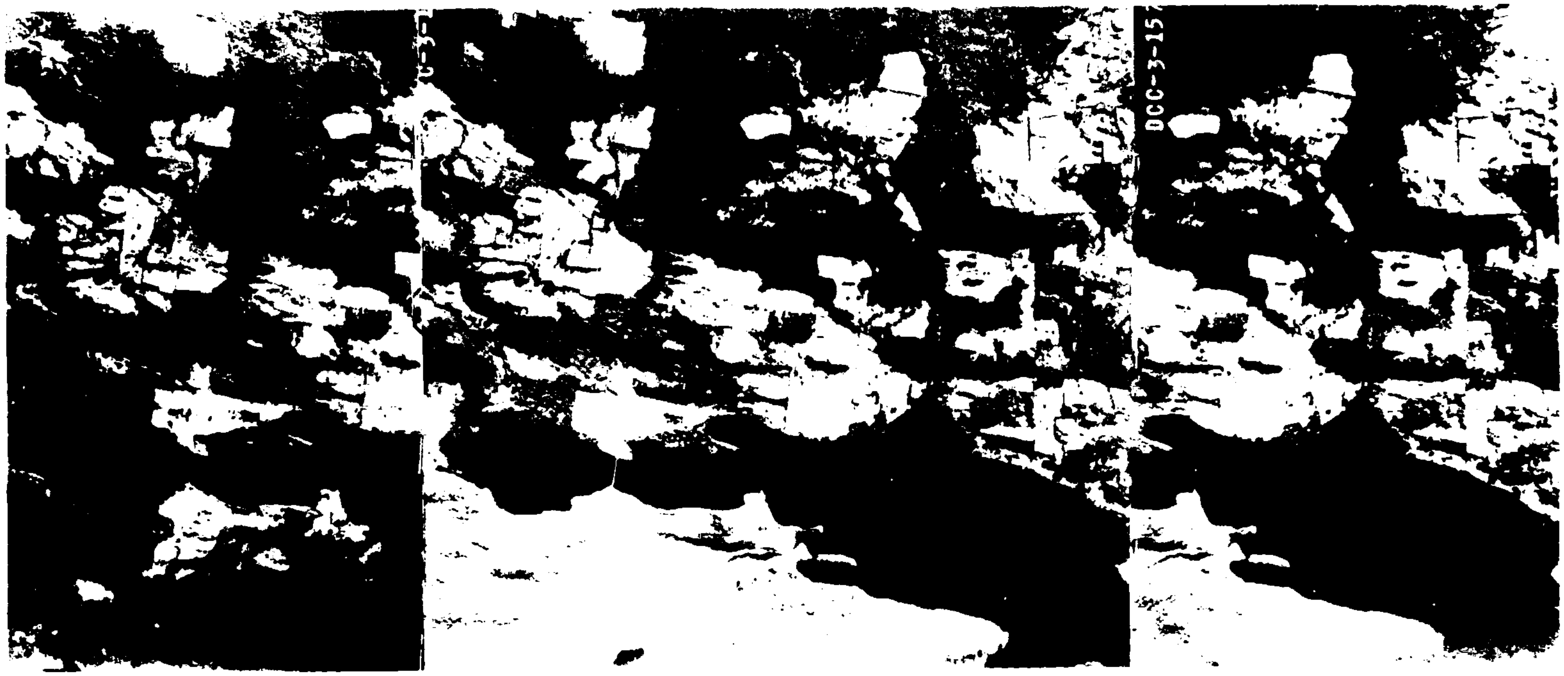


FIGURE 5. Stereotriplet of the Vermont area.
North is to the left, and the scale is approximately
1:46,700 or 1" = 1.2 kilometers.

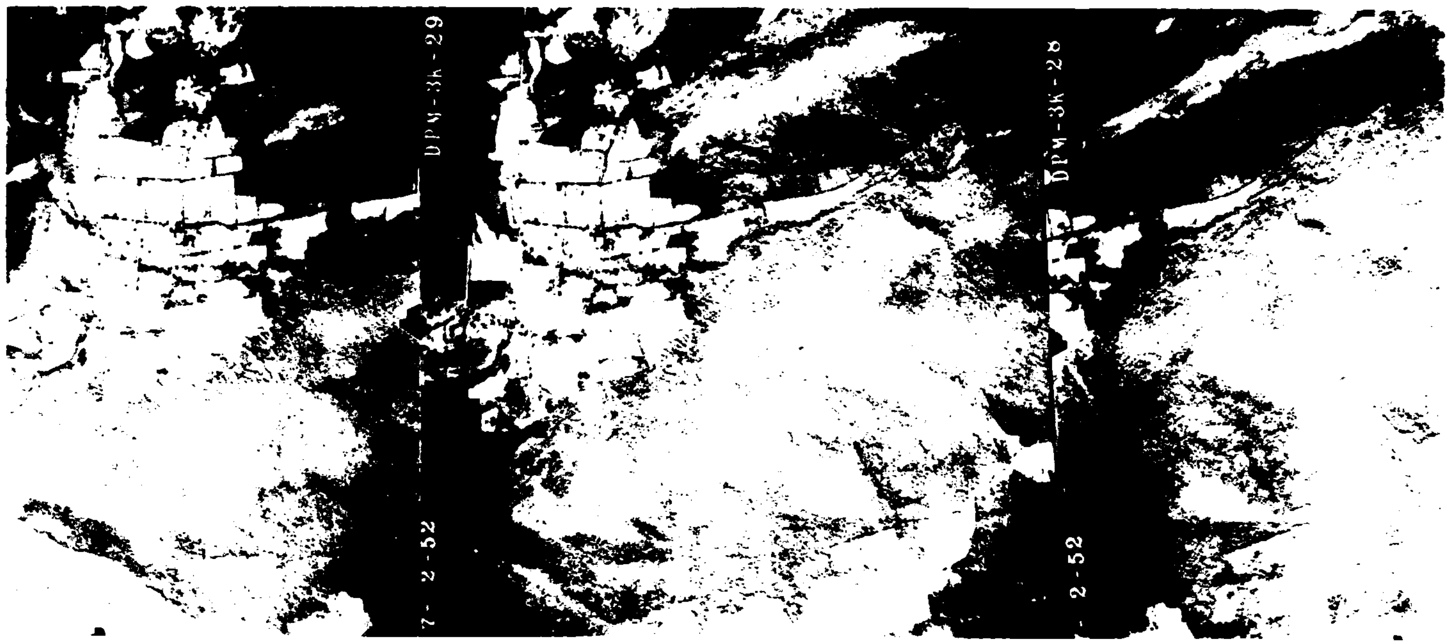


FIGURE 6. Stereotriplet of the Massachusetts area.
North is to the left, and the scale is approximately
1:55,400 or 1″ = 1.5 kilometers.

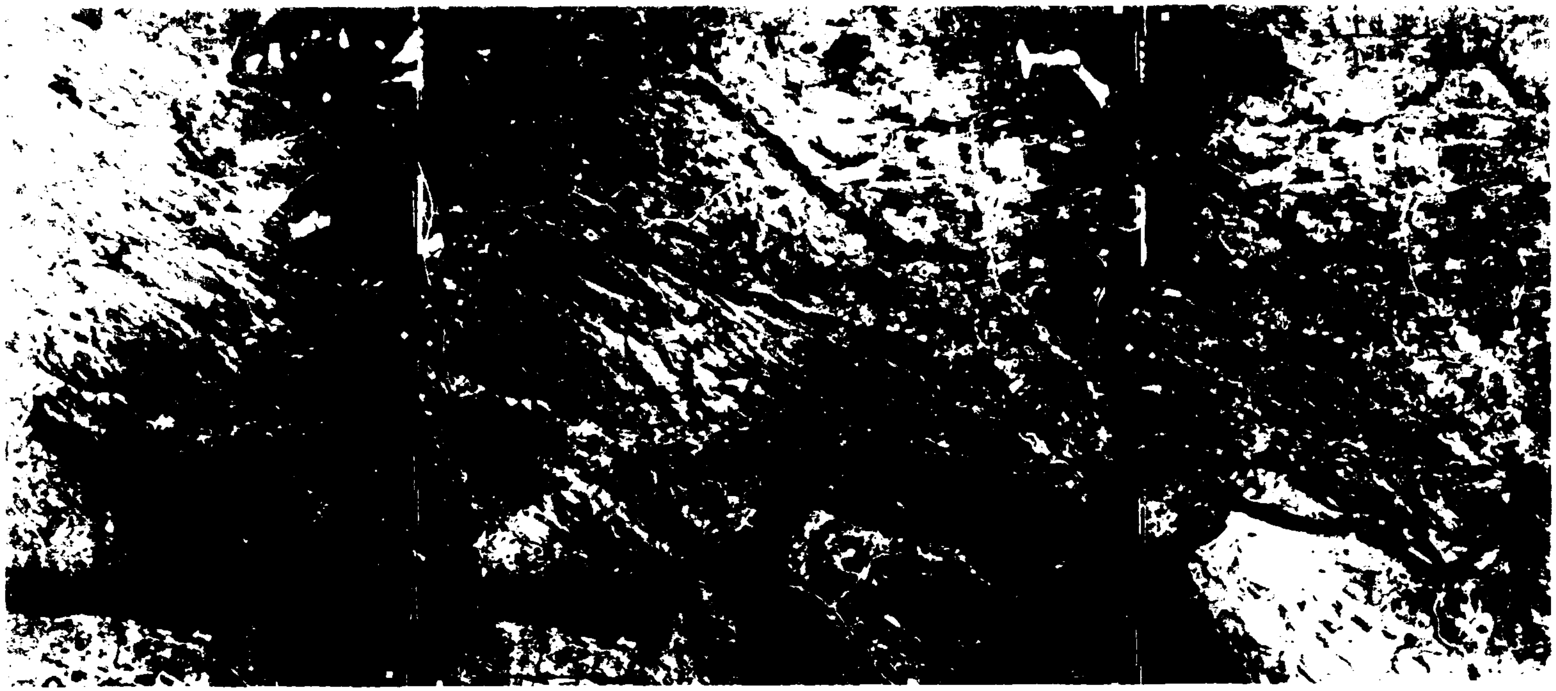


FIGURE 7. Stereotriplet of the West Point, New York area, 1:120,000 scale photo analysis. North is to the left as indicated by the arrow. Scale of this image is approximately 1:280,000 or 1" = 7.3 kilometers.

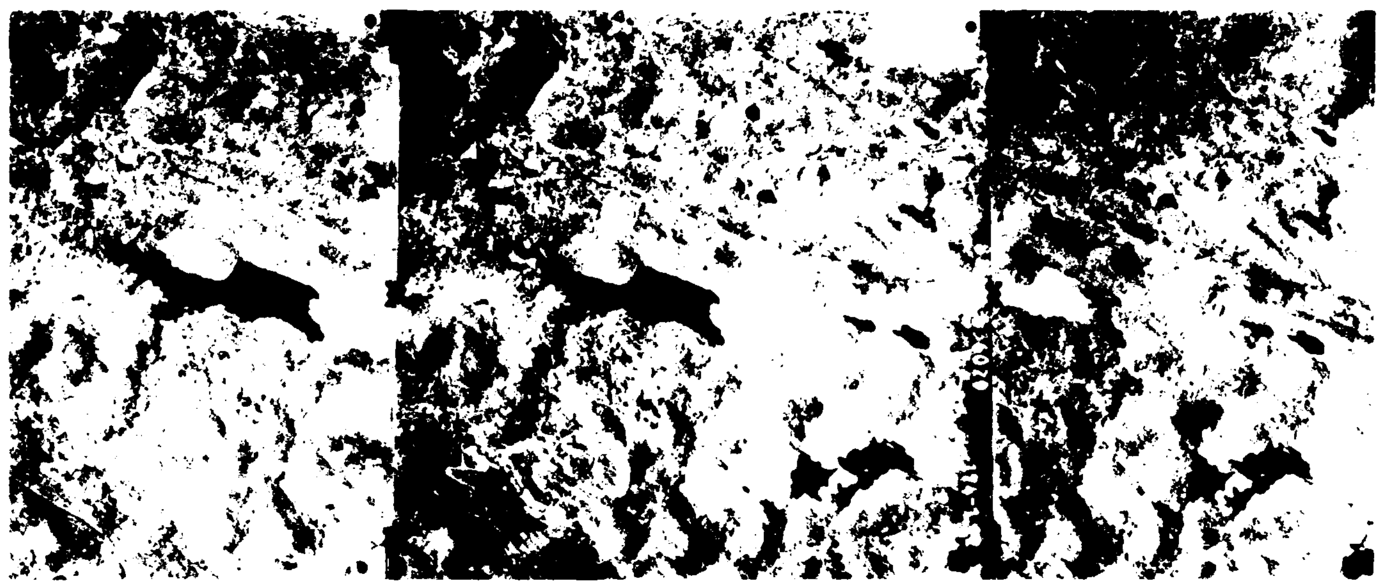


FIGURE 8. Stereotriplet of the West Point, New York, area, 1:35,000 scale. North is to the right as indicated by the arrow. Scale of this image is approximately 1:96,900 or 1" = 2.5 kilometers.

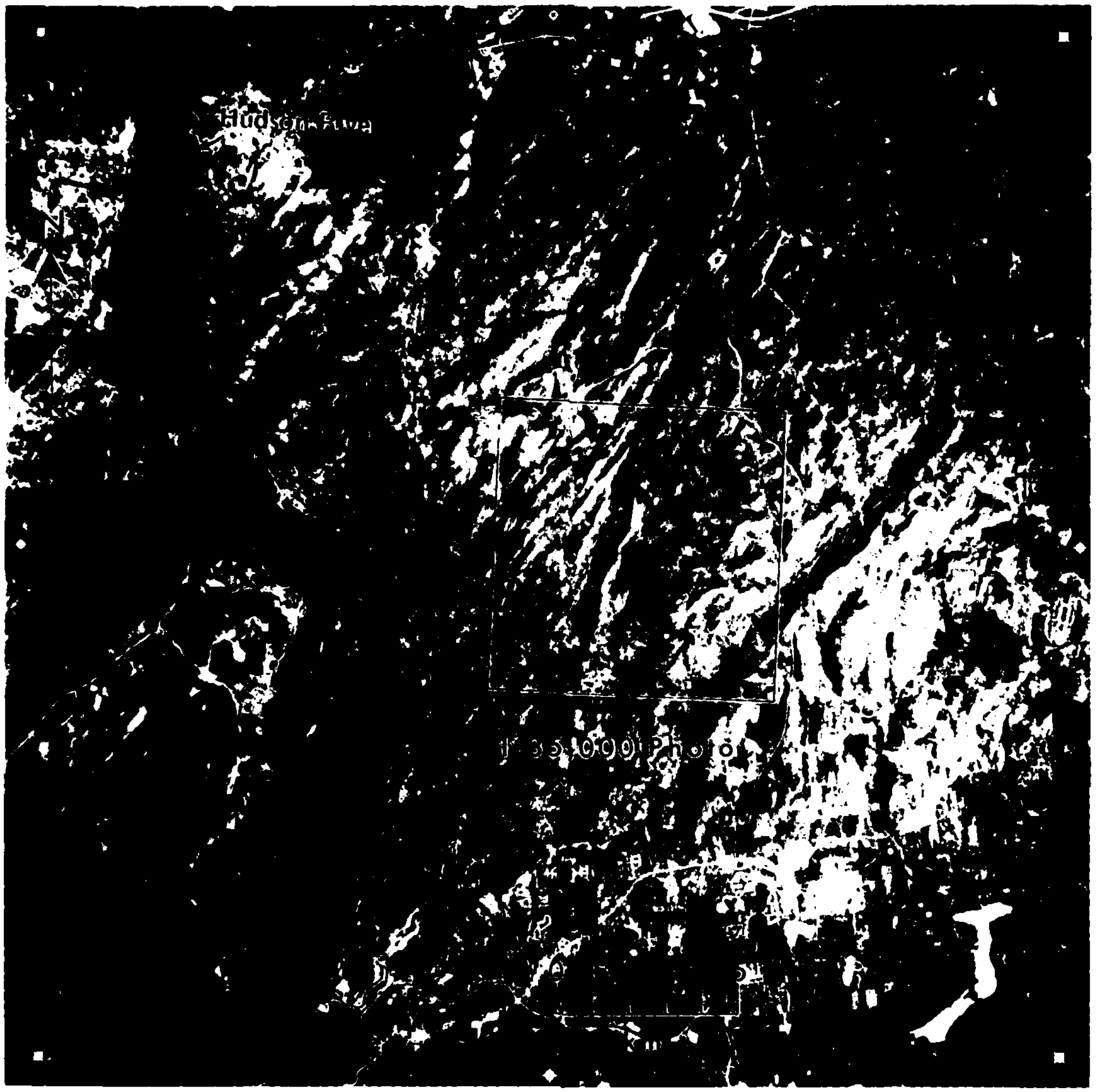


FIGURE 9. Index map showing the location of the center photo of the 1:35,000 scale stereotriplet to the center photo of the 1:120,000 scale stereotriplet.

FIGURE 10. Photo mapping units in the Vermont area. See tables 4 and 8 for predicted rock names and facies.

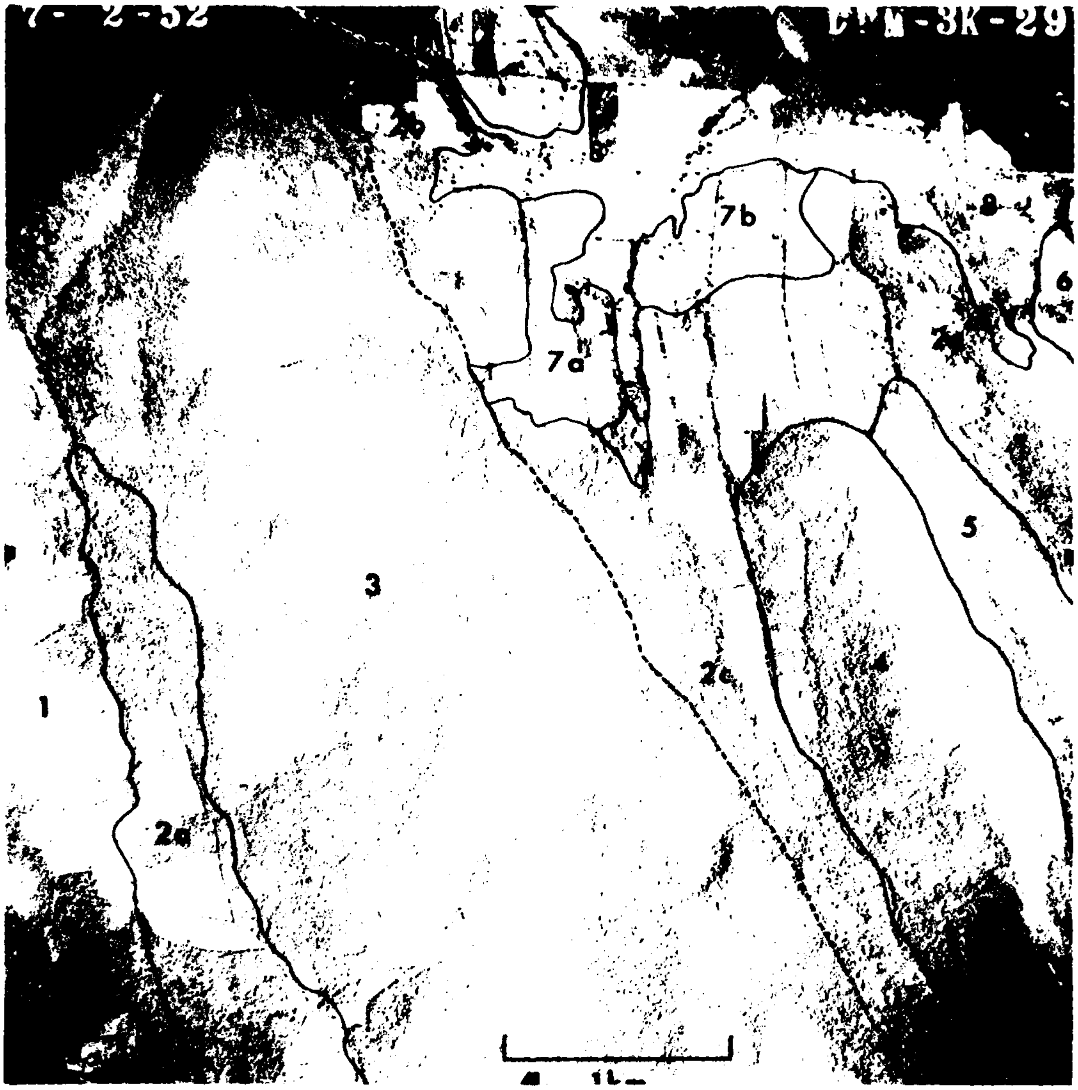


FIGURE 11. Photo mapping units in the Massachusetts area.

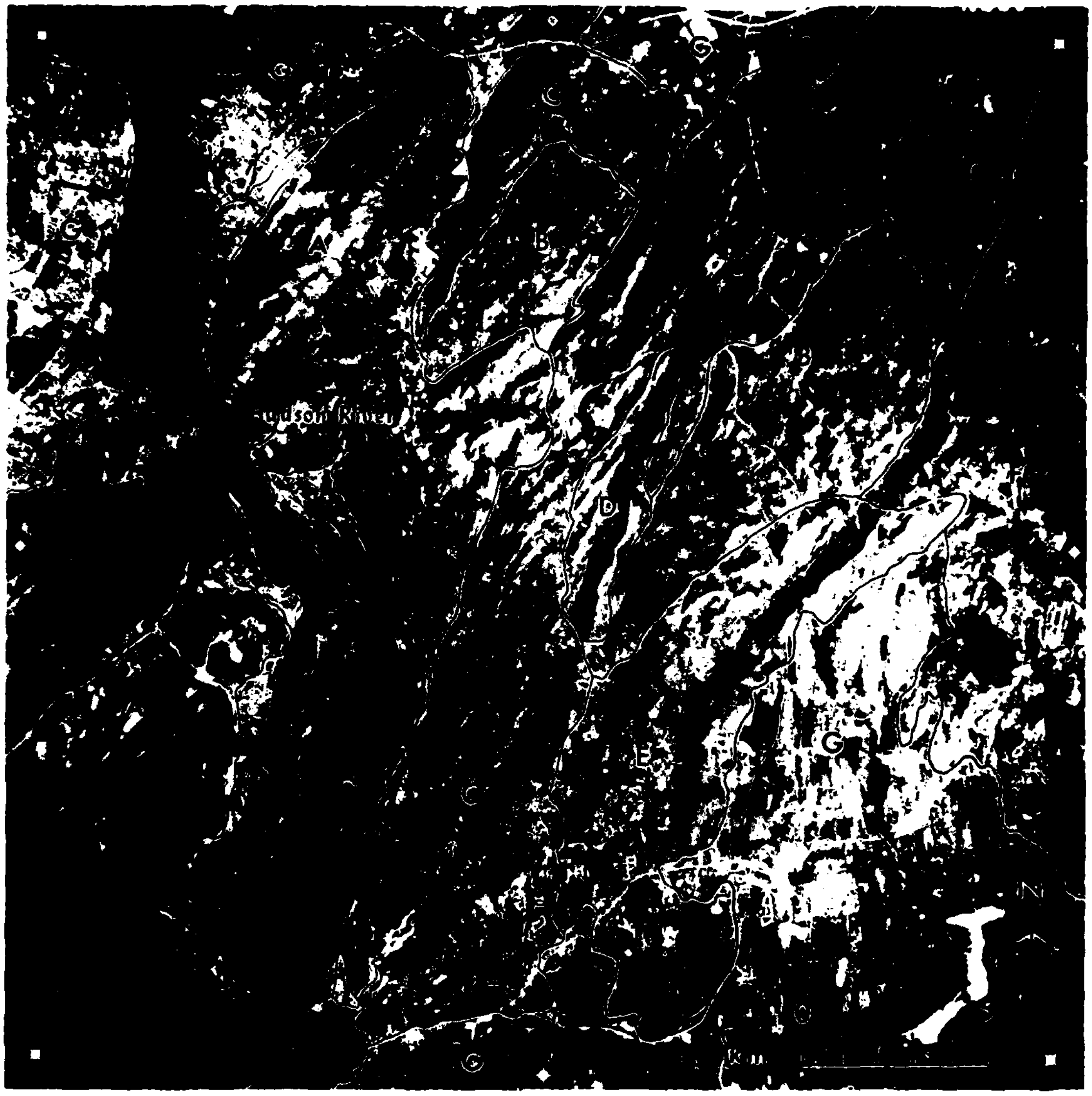


FIGURE 12. Photo mapping units in the West Point, New York, area, 1:120,000 scale. See tables 5 and 9 for predicted rock names and predicted facies.

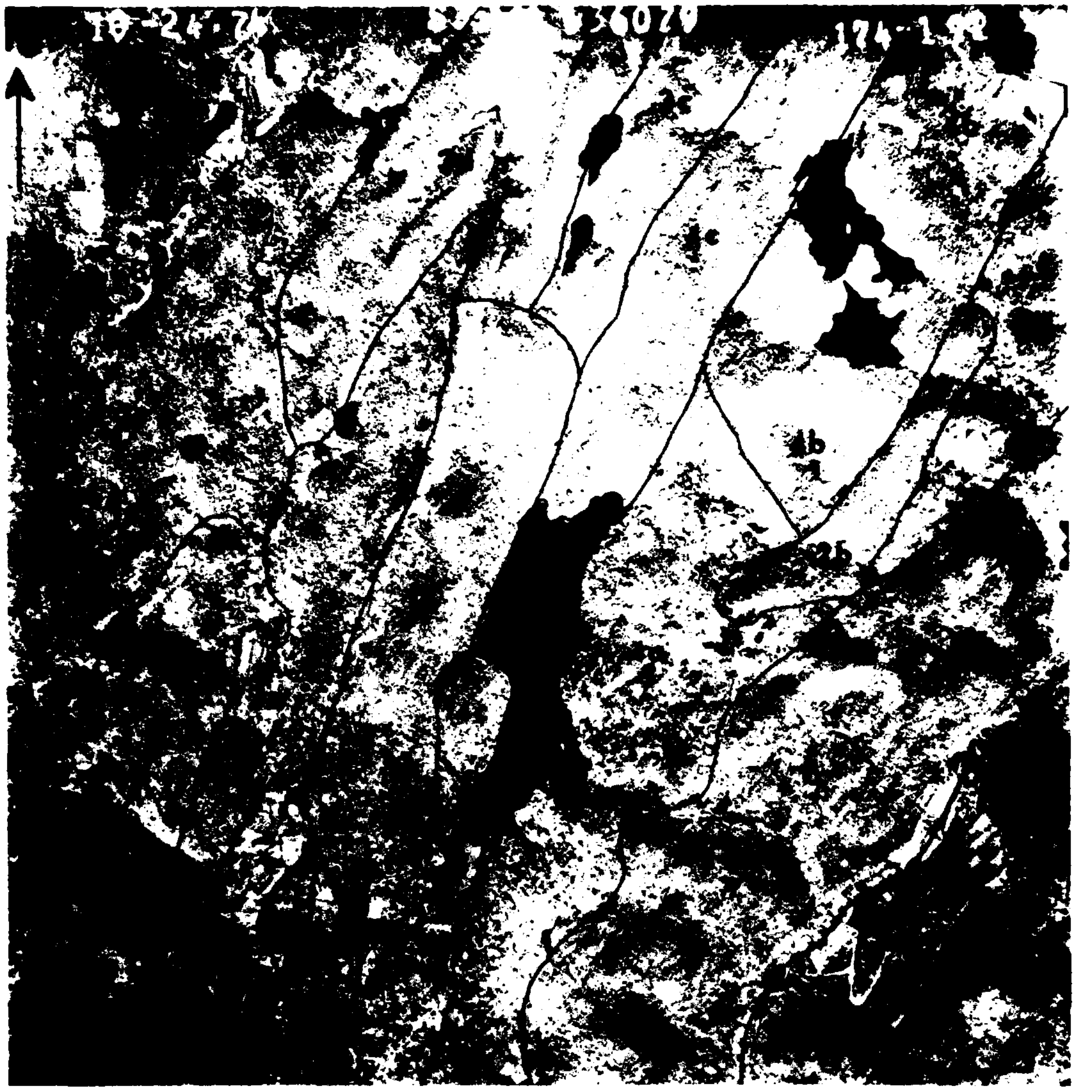


FIGURE 13. Photo mapping units in the West Point, New York, area, 1:35,000 scale. See tables 6 and 10 for predicted rock names and predicted facies.

Table 2 shows which classifications were evaluated in each study area. The textural classification was evaluated in three photo analyses by comparing the pattern element descriptions for each photo mapping unit to published pattern element descriptions for five types of metamorphic rocks; gneiss, schist, slate, marble, and serpentine (Belcher and others, 1951; von Bandat, 1962; Way, 1973; Ehlen, 1983). The most likely rock name for each pattern element was selected, and the most common pattern element name was chosen as the photo mapping unit name. These predicted names were then compared to field observations and published geologic maps for verification. Adaptions of the geologic maps used for verification in the Vermont area and for the 1:35,000 scale West Point analysis are shown in figures 14 and 15. These maps have been scaled to match figures 10 and 13, and labels have been modified to simplify direct comparisons with the photo analyses. Geologic maps corresponding to the 1:120,000 scale West Point area analysis are shown in Ehlen (1983).

TABLE 2. The use of the classification systems for metamorphic rocks in the three study areas

Area	Textural	Formational	Facies
Vermont	+	+	+
Massachusetts		+	
West Point, New York			
1:120,000 scale analysis	+		+
1:35,000 scale analysis	+		+

Prior to this study, there were no attempts to identify metamorphic facies by air photo interpretation procedures. As a result, the facies names applied to the photo mapping units are, at best, educated guesses based on unproven assumptions. The mapping units in the three photo analyses in which the facies classification was used were first ranked from highest to lowest in terms of probable metamorphic grade by determining comparative resistance to erosion in each area. The most improtant pattern elements for this evaluation are landform and drainage.* For example, a mapping unit that consists of hills, has angular and straight rather than curved forms, and that has visible outcrop would be interpreted as consisting of hard material. Conversely, a mapping unit that forms valleys, has gently rounded slopes and a high-density drainage pattern, has

*Other factors, such as lithology and structure, do affect resistance to erosion, but these factors are, in practice, included within landform as used here.

FIGURE 14. Geologic map of the Vermont area, adapted from Zen (1961). A is the Biddie Knob Formation, chloritoid-bearing purple and green slate and phyllite; B, the Mettawee slate member of the Bull Formation, purple, green-gray and varigated slate and phyllite; C, the Zion Hill quartzite member of the Bull Formation; D, the West Castleton Formation, black, graphitic, pyritiferous slate and phyllite; and E, the Mudd Pond Quartzite member of the Bull Formation.

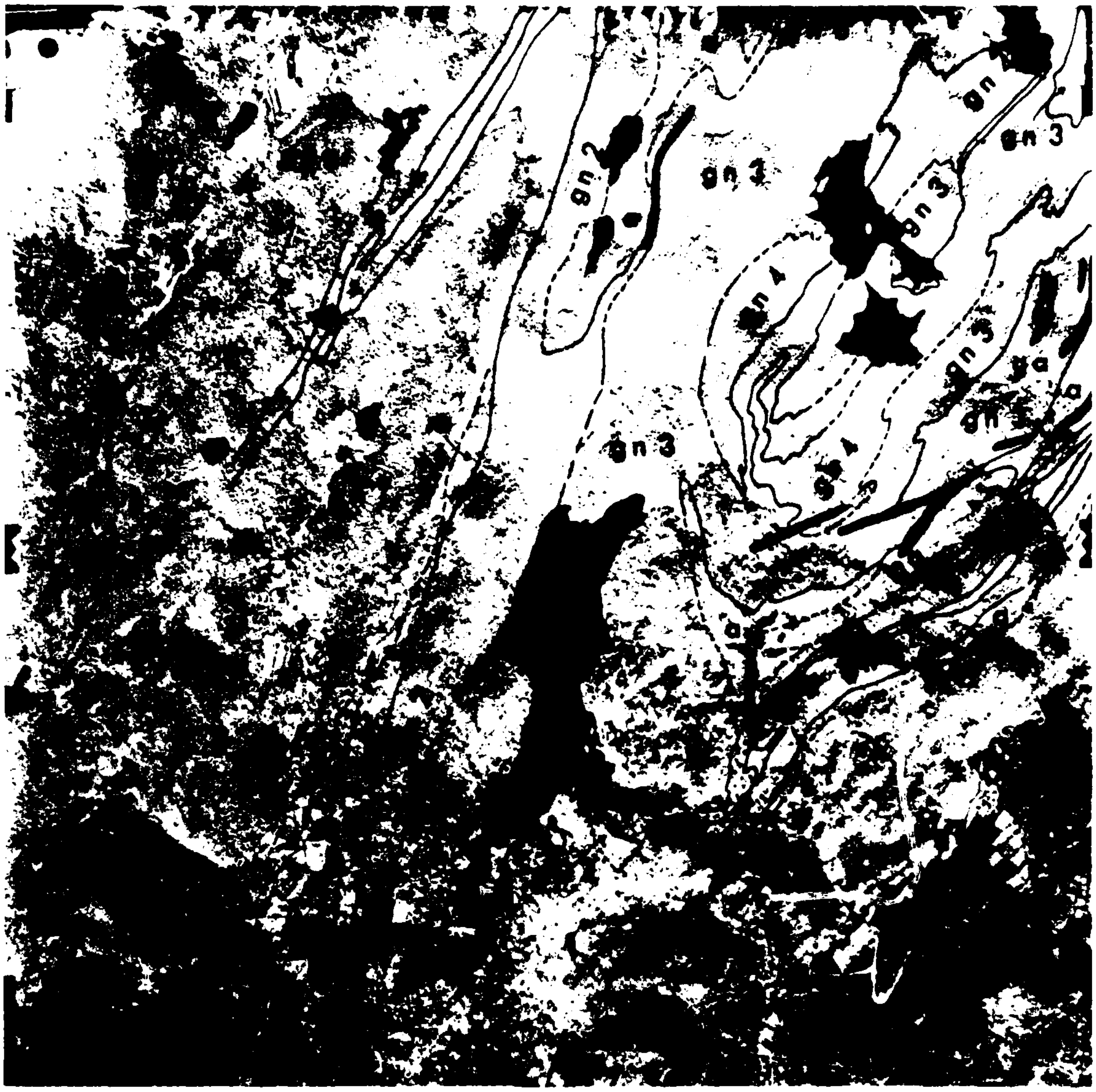


FIGURE 15. Geologic map of the West Point, New York, area, 1:35,000 scale photo analysis, adapted from Ratcliffe (USGS unpublished data). Unit gngr is gneiss and granite; gn 1, quartz plagioclase gneiss; gn 2, hornblende granite gneiss; gn 3, granite gneiss; gn 4, hornblende diorite gneiss; gn 5, biotite gneiss; a, amphibolite; s, schist; ga, gabbro; dotted pattern, pegmatite dikes; solid pattern, mafic dikes.

curved rather than straight forms, and no visible outcrop would be interpreted as consisting of soft material. The first of these mapping units would have a higher resistance to erosion than the second mapping unit. The least-resistant mapping units were assumed to be lowest in metamorphic grade, and the most-resistant units, highest in grade. Low-grade rocks were in turn assumed to be of low facies (pumpelleyite/prehnite or greenschist); whereas, high-grade rocks were assumed to be of higher facies (amphibolite or granulite). Specific facies names were then applied accordingly, and the predictions were compared to the literature for verification. The facies classification was difficult to verify because such information is usually not presented on geologic maps and because facies often vary within formational or textural units. Table 3 shows the regional metamorphic facies (Barrovian-type metamorphism) and the approximate conditions under which each facies is thought to form.

TABLE 3. Metamorphic facies and the approximate conditions under which they form

Facies		Temperature, °C[1]	Pressure, kb[1]
Pumpelleyite/prehnite		Below 350	3–5
Greenschist	Lower	300-350/400	3–8
	Upper	350-400/500	3–8
Amphibolite[2]	Lower	450/500-550	3–8
	Upper	550-650/700	3–8
Granulite		Above 650	3–12

The formational approach was tested in two photo analyses by comparing the photo mapping unit boundaries to formational contacts on published geologic maps. The geologic maps were enlarged to photo scale and superposed on the overlays; the boundaries were compared visually. The geologic maps used for verifying formational boundaries are shown in figures 14 and 16.

[1]Winkler, H.G.F. 1979. *Petrology of Metamorphic Rocks*, 5th edition: Springer-Verlag New York, Inc., 348 p.; Schiffman, P. and Liou, J.G. 1980. "Synthesis and stability relations of Mg-Al pumpelleyite, $Ca_4Al_5MgSi_6O_{21}(OH)_7$." *Jounal of Petrology*, vol. 21, p. 441–474.

[2]The term "amphibolite" is used in two ways. Amphibolite facies rocks are defined in this table; amphibolites are metamorphic rocks that contain 50% or more of an amphibole mineral, usually hornblende. Amphibolites are usually either amphibolite or granulite facies.

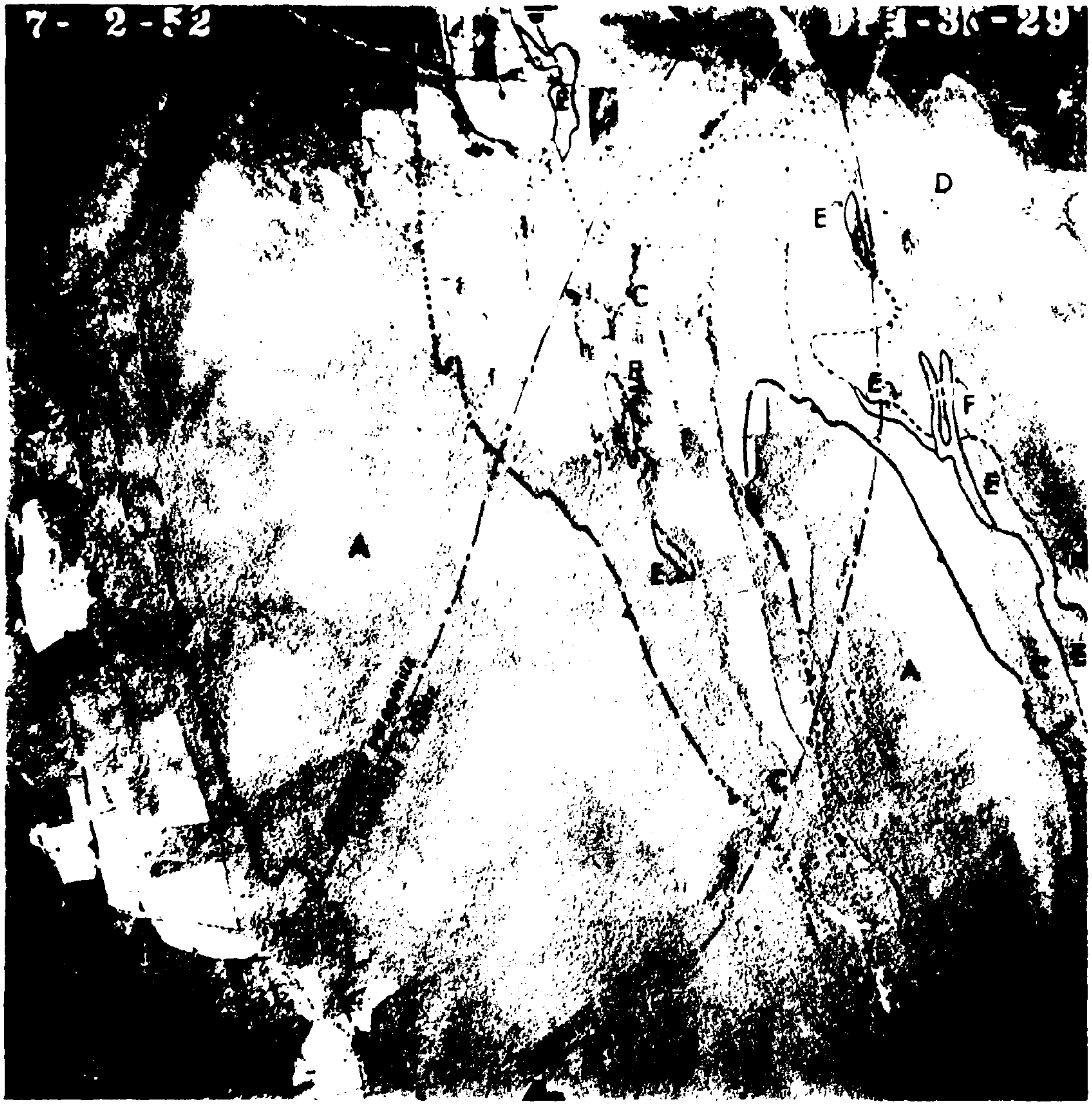


FIGURE 16. Geologic map of the Massachusetts area, adapted from Zen and Hartshorn (1966) and Zen and Ratcliffe (1971). Unit A is the Everett Formation, green and gray-green phyllite; B, the Egremont Phyllite, black to gray slate and phyllite; C, the Stockbridge Formation (g member), calcitic marble; D, also calcitic marble of the Stockbridge Formation (e member); E, sandstone, limestone, and quartzite of the Stockbridge Formation (f member); and F, the Walloomsac Formation, black to gray phyllite and slate.

RESULTS

Textural Classification*

Rock names predicted by using the textural classification are compared to rock names from geologic maps in tables 4, 5, and 6. None of the predicted rock names for the Vermont area (table 4) are correct, but three, those for mapping units 1, 4, and 5, are partly correct.** Table 5 shows the rock names predicted in the 1:120,000 scale photo analysis of the West Point, New York, area compared to rock names from geologic maps. Two of the six predictions are correct, and one is partly correct. No prediction was made for unit G because it was thought to be sedimentary rock. The names predicted in the 1:35,000 scale photo analysis of the West Point, New York, area are shown in table 6; two of the five predictions are correct. No prediction was made for unit 2 because the pattern element descriptions for this mapping unit were very different from the descriptions in the published criteria and no name could be chosen.

TABLE 4. Predicted textural rock names compared to names from geologic maps: Vermont area

Mapping Unit	Predicted Name	Geologic Map Name[1]
1	Schist or marble	Slate and phyllite
2	Gneiss	Quartzite, graywacke, arkose
3	Marble	Slate and phyllite
4	Schist, marble, or gneiss	Slate and phyllite
5	Gneiss or schist	Slate and phyllite
6	Schist	Slate

*The data presented here, along with additional data, are discussed in more detail in Ehlen (1983).

**Phyllite is between slate and schist in grade, and because it is not included in the published identification criteria for metamorphic rocks, predictions of either slate or schist were considered partly correct when the rock type was phyllite.

[1]Zen, E-an. 1961. "Stratigraphy and structure at the north end of the Taconic Range in west-central Vermont." *Geological Society of America Bulletin*, vol. 72, pp. 293–338.

TABLE 5. Predicted textural rock names compared to names from geologic maps: West Point 1:120,000 scale analysis

Mapping Unit	Predicted Name	Geologic Map Name[1]
A	Gneiss	Gneiss
B	Granite	Gneiss and granite
C	Schist	Granite and gneiss
D	Slate	Gneiss
E	Gneiss	Gneiss
F	Schist	Gneiss
G	No prediction made	Gneiss

[1]Dodd, R.T., Jr. 1965. Precambrian geology of the Popolopen Lake quadrangle, New York: New York State Museum and Science Service, Map and Chart Series, no 6; Helenek, H.L. and Mose, D., 1976, Structure, petrology and geochronology of the Precambrian rocks in the Central Hudson Highlands: *IN* Johnson, J.H. (ed), *Guidebook to Field Excursions*, 48th Annual Meeting of the New York State Geological Association, pp B-1-1 to B-1-27; Ratcliffe, N.M. and Helenek, H.L., Bedrock geology of the Peekskill quadrangle, New York: U.S. Geological Survey Bulletin (in preparation); Ratcliffe, N.M., USGS unpublished data.

TABLE 6. Predicted textural rock names compared to names from geologic maps: West Point 1:35,000 scale analysis

Mapping Unit	Predicted Name	Geologic Map Name[1]
1	Schist	Gneiss
2	No prediction made	Gneiss
3	Slate or schist	Granite and gneiss
4	Gneiss	Gneiss
5	Schist	Marble
6	Gneiss	Gneiss

[1]Ratcliffe, N.M. USGS unpublished data.

Table 7 summarizes the degree of success achieved using the textural classification by combining the data from the three photo analyses. Nineteen percent of the predictions were correct; 14 percent were partly correct; and 67 percent were wrong.* The correct predictions were all for gneissic rocks.

TABLE 7. Success achieved using the textural classification

Rock Type	Number of Predictions	Percent Correct	Percent Partly Correct	Percent Wrong
Gneiss	7	57	0	43
Schist	9	0	33	67
Marble	3	0	0	100
Slate	2	0	0	100

Facies Classification

Predicted facies names are compared to actual facies names in tables 8, 9, and 10. The predictions for the Vermont area are shown in table 8. Facies were correctly predicted for unit 1, and the prediction for unit 3 was partly correct.

TABLE 8. Predicted facies compared to actual facies for the Vermont area

MAPPING UNIT	Predicted Facies	Actual Facies[1]
1	Lower greenschist	Lower greenschist
2	Lower amphibolite	Lower greenschist
3	Upper greenschist	Lower greenschist
4	Upper amphibolite	Lower greenschist
5	Upper amphibolite	Lower greenschist
6	Upper amphibolite	Lower greenschist

*A prediction was considered partly correct if the predicted rock type or one of the predicted rock types was included as one of the major rock types on the geologic map.

[1]Zen, personal communication, 1982.

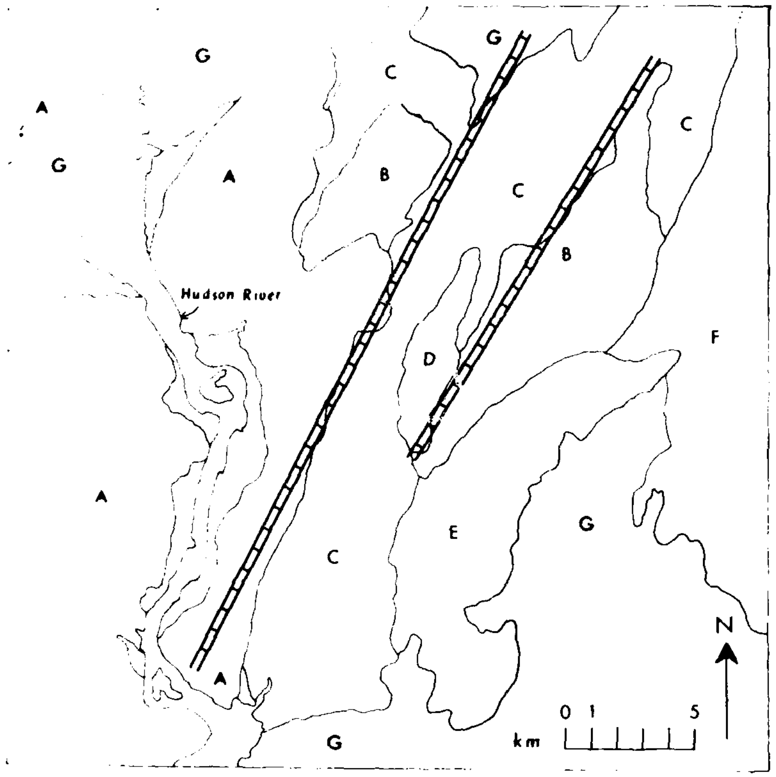
In the West Point 1:120,000 scale analysis, all the facies predictions were not only incorrect, they were also consistently too low (table 9). No predictions were made for units B and G because they were thought to be igneous and sedimentary rock, respectively; unit E was thought to be quartzite. The order of the mapping units in terms of grade was accurately determined by air photo analysis, but the position of the predictions within the facies classification was too low. Units A and D, for instance, were correctly predicted as the highest and lowest units, respectively, in metamorphic grade; but rather than being amphibolite facies as predicted, unit A is granulite facies. Unit D was predicted to be pumpelleyite/prehnite or lower greenschist facies, but it actually is amphibolite facies.

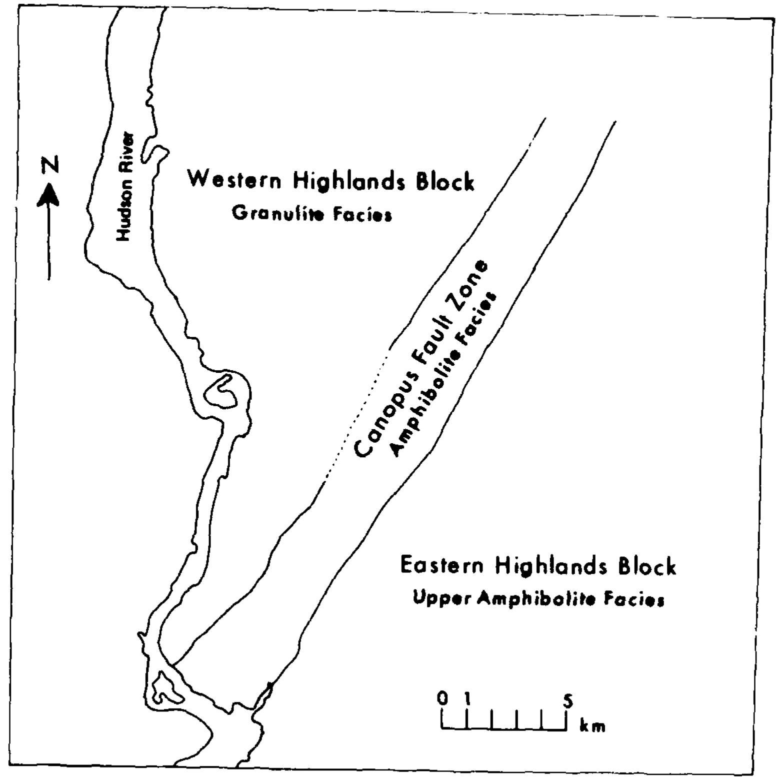
TABLE 9. Predicted facies compared to actual facies for the 1:120,000 scale West Point analysis

Mapping Unit	Predicted Facies	Actual Facies[1]
A	Amphibolite	Granulite
B	No prediction made	Granulite and upper amphibolite
C	Upper greenschist	Amphibolite
D	Pumpelleyite/prehnite or greenschist	Amphibolite
E	No prediction made	Upper amphibolite
F	Upper greenschist	Upper amphibolite
G	No prediction made	Upper amphibolite

There is, however, a high degree of correspondence between the regional distribution of the two facies and some of the boundaries between photo mapping units. Figure 17 illustrates these relationships. A line along the eastern boundaries of photo mapping units A and the western part of B corresponds to the boundary between the granulite facies rocks of the Western Highlands Block and the amphibolite facies rocks of the Canopus Fault Zone (Ratcliffe, USGS unpublished data). The fault zone itself corresponds roughly to most of unit C and to unit D. The eastern boundaries of these two units separate the amphibolite facies rock of the fault zone proper from the upper amphibolite facies rocks of the Eastern Highlands Block, e.g. the eastern part of unit B, parts of unit C, and units E, F, and most of unit G.

[1]Helenek, H.L. and Mose, D. 1976. Structure, petrology, and geochronology of the Precambrian rocks in the Central Hudson Highlands: *IN* Johnson, J.H. (ed), *Guidebook to Field Excursions,* 48th Annual Meeting of the New York Geological Association, pp B-1-1 to B-1-27; Ratcliffe, N.M., USGS unpublished data.





A. Photo mapping units. Heavy lines indicate the approximate boundaries of the Canopus Fault zone.

B. Metamorphic facies.

FIGURE 17. Relations between photo mapping units and metamorphic facies, 1:120,000 scale photo analysis of the West Point, New York, area.

Table 10 shows the facies predictions made in the 1:35,000 scale photo analysis of the West Point, New York, area; one prediction was correct (unit 6) and one was partly correct (unit 1).

TABLE 10. Predicted facies compared to actual facies for the 1:35,000 scale West Point analysis

Mapping Unit	Predicted Facies	Actual Facies[1]
1	Lower amphibolite	Granulite and upper amphibolite
2	No prediction made	Amphibolite
3	Lower amphibolite	Granulite
4	Upper greenschist	Amphibolite
5	Upper greenschist	Amphibolite
6	Upper amphibolite	Upper amphibolite

Table 11 summarizes the success achieved using the facies classification. In this table, the predictions made in all three photo analyses are combined. A total of 16 predictions of metamorphic facies were made, but only two of them, or about 13 percent, were correct. An additional two predictions were partly correct.

TABLE 11. Success achieved using the facies classification

Facies	Numer of Predictions	Percent Correct	% Partly Correct	Percent Wrong
Pumpelleyite/prehnite	1	0	0	100
Lower greenschist	2	50	50	0
Upper greenschist	5	0	0	100
Lower amphibolite	3	0	0	100
Upper amphibolite	4	25	25	50
Amphibolite	1	0	0	100

[1] Ratcliffe, USGS unpublished data.

Formational Approach

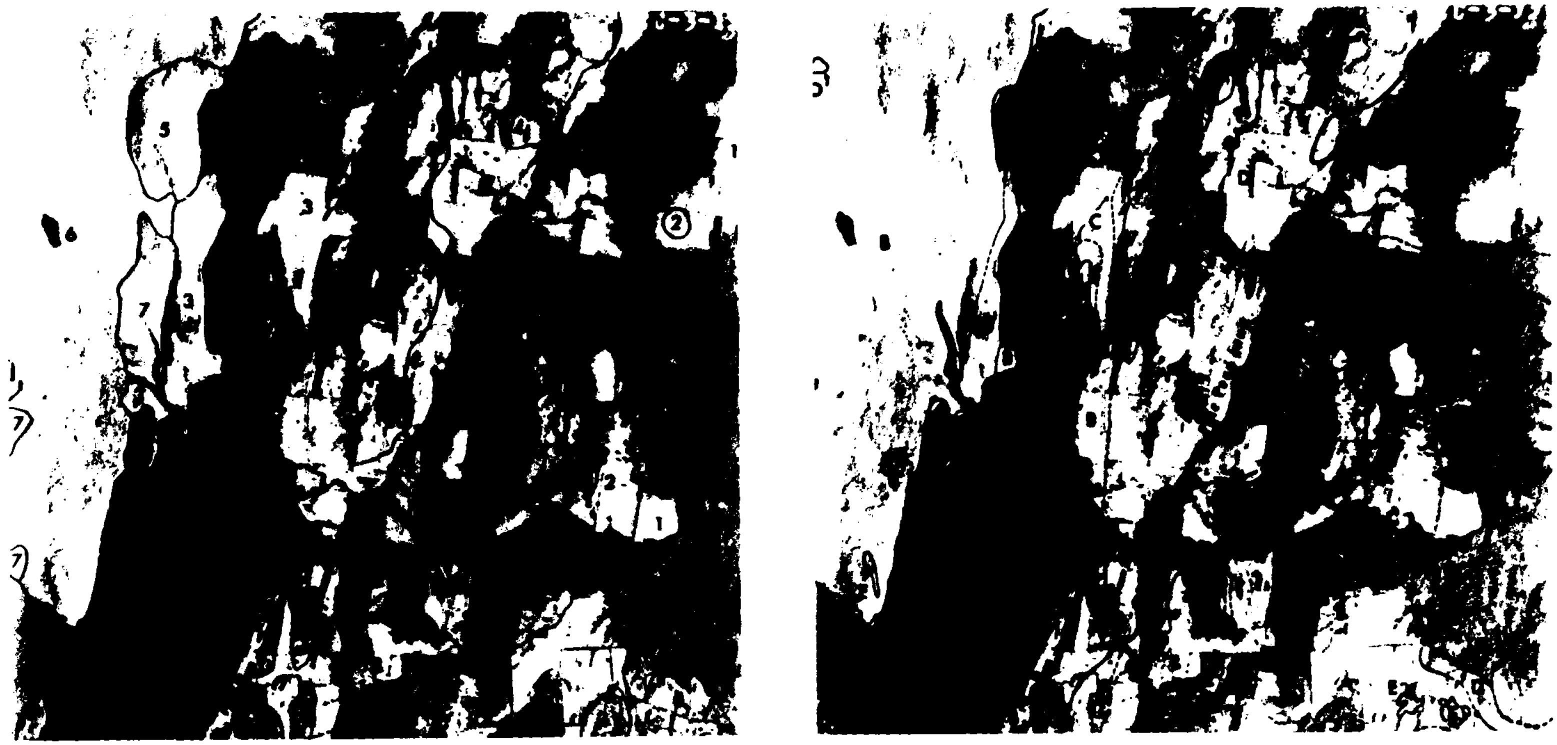
Vermont Area. Table 12 shows the relations between photo mapping units and geologic formations in the Vermont area. The only direct correlation on table 12 is between the Zion Hill Quartzite (Unit C) and photo mapping unit 2. The multiple relationships between the remaining formations and mapping units result from slight differences in landform pattern owing partly to glacial action and partly to changes in attitude and structural repetitiveness, e.g. the same formations are repeated across the photos from east to west.

TABLE 12. Relations between photo mapping units and geologic formations in the Vermont area

Formations:[1]	Photo Mapping Units: 1	2	3	4	5	6
Biddie Knob Formation (A, slate and phyllite)	+					
Mettawee slate (B)	+		+			+
Zion Hill Quartzite (C)		+				
West Castleton Formation (D, slate and phyllite)			+	+	+	

Most of the landform unit boundaries, however, correspond quite closely to formational boundaries on the geologic map (figure 18B; adapted from Zen, 1961). The Biddie Knob Formation (unit A) was the only formation that was not discriminated, at least in part, on the air photos. It was included as part of photo mapping unit 1, which is formed primarily of the Mettawee slate. Both the Biddie Knob and the Mettawee slate consist of similar purple and green slates and phyllites, but they can be differentiated under magnification, and according to Zen (personal communication, 1982), the two have slightly different resistances to erosion; the Biddie Knob Formation is slightly less resistant than the Mettawee slate. Discrepancies, as stated above, are due to changes in landform patterns. For instance, photo mapping unit 3 is composed of drumlins, a landform caused by glacial action that is independent of the underlying material.

[1] Zen, E-an. 1961. "Stratigraphy and structure at the north end of the Taconic Range in west-central Vermont." *Geological Society of America Bulletin,* vol. 72, pp. 293–338.



A. Photo Mapping Units.

B. Geologic Map.

FIGURE 18. Comparison of photo mapping unit boundaries and geologic contacts, Vermont area.

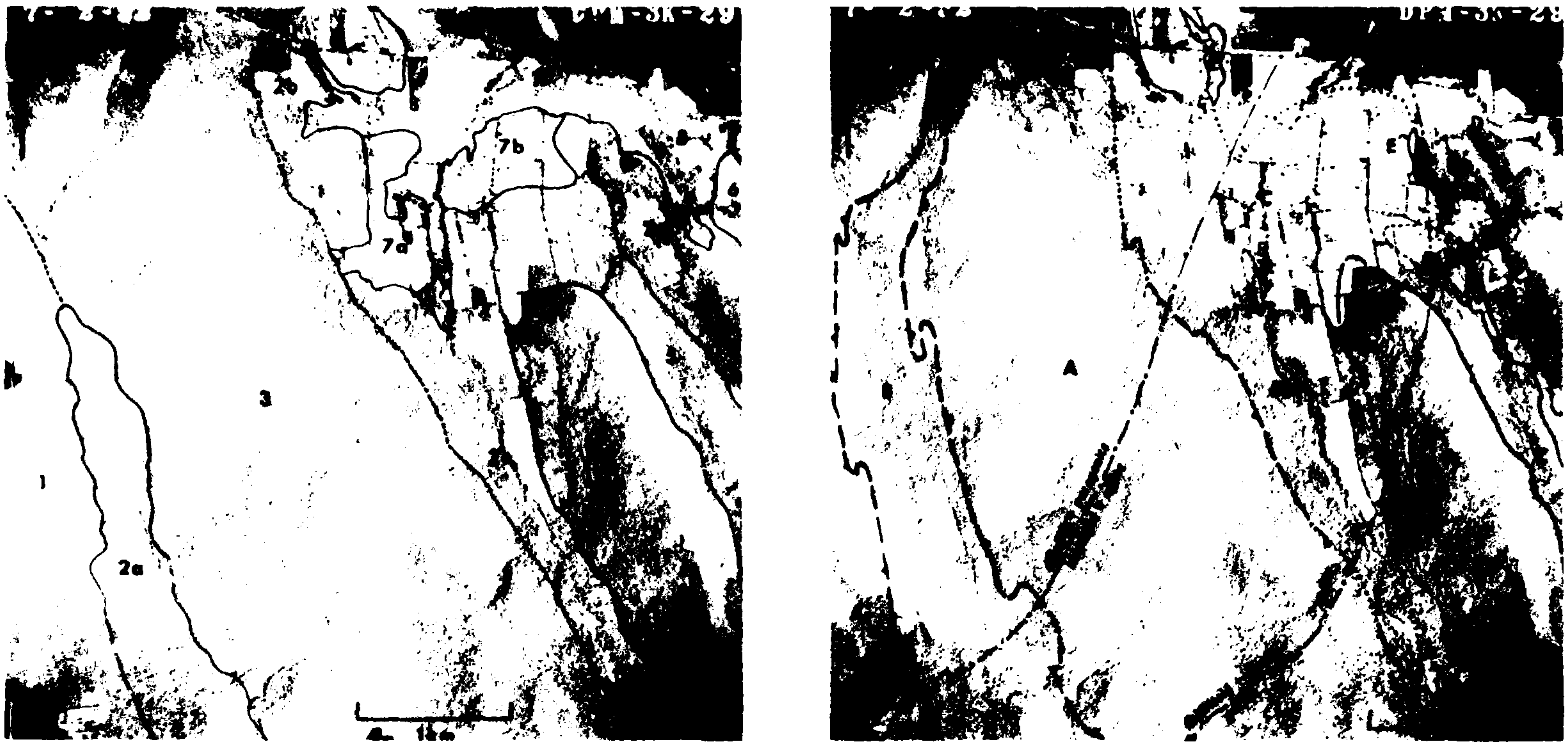
Massachusetts Area. Table 13 shows the relationships between photo mapping units and geologic formations in the Massachusetts area. Only two photo mapping units, 2c and 6, occur in more than one formation, but all formations, except the Egremont Phyllite (unit B), contain at least three photo mapping units. In other words, although the formational boundaries were delineated as landform boundaries in photo analysis, more than one landform unit occurs in each formation. Some landform differences within a formation result from glaciation; whereas, others are caused by changes in attitude or dip.

TABLE 13. Relations between photo mapping units and geologic formations in the Massachusetts area

Formations:[1]	Photo Mapping Units: 1	2a	2b	2c	2d	3	4	5	6	7a	7b	8
Everett Formation (A, phyllite)	+					+	+					
Egremont Phyllite (B)		+										
Stockbridge Formation, g member (C, marble)			+	+				+	+	+	+	
Stockbridge Formation, e member (D, marble)				+	+				+			+

The formations composed of marble were differentiated from the phyllite units on the photo mapping unit overlay, and in addition, two different marbles and two different phyllites were discriminated (figure 19; adapted from Zen and Hartshorn, 1966; and Zen and Ratcliffe, 1971). The Everett Formation (unit A) contains more abundant and thicker sandy layers than the Egremont Phyllite (unit B), which explains why it has more topographic expression; it is more resistant to erosion. Similarly, the numerous, thick dolostone layers in the g member of the Stockbridge Formation (unit C) makes it more resistant to erosion than the e member, which contains only small amounts of thin-bedded dolostone.

[1]Zen, E-an and Hartshorn, J.H. 1966. Geologic map of the Bashbish Falls quadrangle, Massachusetts, Connecticut, and New York: U.S. Geological Survey GQ-507; Zen, E-an and Ratcliffe, N.M. 1971. Bedrock geology of the Egremont quadrangle and adjacent areas, Berkshire County, Massachusetts and Columbia County, New York: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-628. Geologic mapping units E (Stockbridge Formation, f member) and F (Walloomsac Formation) are not included in this table because of their small size.



A. Photo Mapping Units.

B. Geologic Map.

FIGURE 19. Comparison of photo mapping unit boundaries and geologic contacts, Massachusetts area.

DISCUSSION

Textural Classification

Names were chosen for most of the mapping units in the Vermont and West Point, New York, areas by using the published identification criteria, which are based on rock texture (Belcher and others, 1951; von Bandat, 1962; Way, 1973; Ehlen, 1983). As stated previously, 21 predictions were made: 19 percent were correct; 14 percent were partly correct; and 67 percent were wrong. In most cases, however, the choices of names were questionable at best; the similarities between photo mapping unit descriptions and the published identification criteria were minimal.* In addition, the percentages of correct predictions were too low to be considered useful: 0 percent in the Vermont area, 33 percent in the 1:120,000 scale West Point analysis, and 40 percent in the 1:35,000 scale West Point analysis.

The textural classification did not work very well, partly because the textures within each area are quite similar and partly because identification criteria do not exist for all the common textural rock types; phyllite, for instance, is not included. Attempting to fit rocks into a format that does not include them was like trying to fit square pegs into round holes. Also, as pointed out previously (Ehlen, 1983), the published criteria are incomplete and are not separated by climate, which would make a significant difference in their application. In addition, the effects of glaciation and of geologic structure on photo pattern are not adequately addressed in the published criteria.

The textural classification as defined by the published criteria was used most successfully with metamorphic rocks of sedimentary, rather than igneous, origin. Textural names were most easily and accurately selected for those rocks indicated to be of sedimentary origin on the geologic maps. The reason for this is unknown, but it is probably related to the fact that identification is easier when photo patterns are more regular and consistent; igneous rocks can be characterized by the absence of order or arrangement in their photo patterns. In addition, this classification system was more successful with higher grade rocks. At least some of the predictions of gneiss and schist were correct or partly correct; whereas, none of the predictions of slate or marble were correct. This probably results from the facts that the higher grade rocks are more extensive geographically and that glacial modifications are greater for the lower grade rocks.

*See Ehlen, 1983, for an evaluation of the published criteria for identifying metamorphic rocks on air photos.

Facies Classification

There are two steps involved in using the facies classification on air photos. First, the rocks must be ranked from lowest to highest in metamorphic grade, and second, the position of the ranked series in relation to the facies classification as a whole must be determined. This classification was tested in the Vermont area and in both analyses of the West Point, New York, area.

Relative grade can be determined on air photos by evaluating the differences in resistance to erosion of the mapping units (Allum, 1960-61; Ehlen, 1981, 1983). This was done correctly for both of the West Point analyses, but not for the Vermont area. Variation in grade in the Vermont area is minimal, and the differences in landform pattern results primarily from lithology and glaciation, not grade. It is interesting to note the consistency with which the predictions in the 1:35,000 scale West Point analysis were made; units 1 and 3, for instance, were predicted to be lower amphibolite facies, but both are granulite facies. The predictions for units 4 and 5, that they are upper greenschist facies, are equally consistent; both photo mapping units are amphibolite facies.

At this point, there is no way to determine precisely, prior to verification, where the range of ranked rocks lies in relation to the facies classification. This is shown well in tables 8, 9, and 10 where only 13 percent of the predictions were correct. All the photo mapping units, except for one in the Vermont area, were placed incorrectly within the facies classification. The range predicted for the Vermont area rocks was from lower greenschist to lower amphibolite facies; whereas, the rocks all belong to the lower greenschist facies. The reverse was true in the 1:120,000 scale West Point analysis; the predicted range was the same as for the Vermont area, but the actual range, within the amphibolite and granulite facies, was significantly higher.

The fact that the various facies were accurately discriminated, although not identified on the 1:120,000 scale West Point photos suggests that a potential exists for using the facies classification in conjunction with air photo analysis. Because the goal of this study is to identify metamorphic rocks on air photos by composition, this small success is encouraging.

Formational Approach

All three classification methods require careful and precise boundary determinations. This process is much more important, however, when using the formational approach because formations are defined in terms of their boundaries as well as lithology; formations do not grade into one another in the same way that textures and facies do. Once the boundaries are satisfactorily determined, rock names are applied usually using the textural classification. The test of the formational approach in the photo analyses of the Vermont and Massachusetts areas was quite successful. Greater success was achieved in the Massachusetts area, however, where the effects of glaciation and geologic structure are less pronounced and where lithic contrasts are greater.

The photo mapping unit boundaries in the Vermont area, although not exact, are very close to the formation boundaries on the geologic map, except where obscured by glacial features. The fact that the mapping units are part of a repetitive sequence was not recognized in the photo analysis, e.g. photo mapping units 1, 3, and 6 are all the Mettawee slate. Because their landform patterns are slightly different, they were mapped separately in the photo analysis. The names provided for the mapping units on the basis of the textural classification were wrong, partly because one of the two most common rock types in the area, phyllite, is not included in the published criteria.

The photo mapping unit boundaries in the Massachusetts area are very accurate in comparison to the geologic maps of the area, indicating that metamorphic rocks can be discriminated on air photos, at least where lithology is constant within the formation and sharply different across formations. No rock names were predicted for the photo mapping units in the Massachusetts area, however, because heavy tree cover obscured much of the drainage pattern as well as the photo tones and photo textures of many of the mapping units.

CONCLUSIONS

1. Of the three metamorphic rock classification schemes evaluated (textural, facies, and formational), only the textural classification has potential for near-future use in identifying specific metamorphic rock types by air photo interpretation procedures.

2. Prior to this study, no work was done relating either the facies classification or the formational approach to rock type identification on air photos.

   a. There is potential for the use of the facies classification, based on evaluation of landform and drainage patterns, but only in the long range, e.g. many man-years of research are required.

   b. The formational approach cannot be used to identify specific rock type, and no basis for future use with reference to air photos was identified.

REFERENCES CITED

Allum, J.A.E. 1960-1961. Photogeological Interpretation of Areas of Regional Metamorphism. *Transactions of the Institution of Mining and Metallurgy*, vol. 70, part 9, pp. 521-543.

von Bandat, H.F. 1962. *Aerogeology*. Houston, Gulf Publishing Co.

Belcher, D.J.; Ta Liang; Costello, R.B.; Fallon, G.J.; Hodge, R.J.; Ladenheim, H.C.; Lueder, D.R.; and Mollard, J.D. 1951. "A Photo Analysis Key for the Determination of Ground Conditions, Landform Reports," vol. 3, *Igneous and Metamorphic Rocks:* Cornell University School of Engineering, Ithaca, NY, for the Amphibious Branch, Office of Naval Research, U.S. Naval Photographic Interpretation Center.

Dodd, R.T., Jr. 1965. "Precambrian Geology of the Popolopen Lake Quadrangle, Southeastern New York." New York State Museum and Science Service, Map and Chart Series No. 6.

Ehlen, J. 1976. *Photo Analysis of a Desert Area.* U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, ETL–0068, AD–A035 481.

Ehlen, J. 1982. *The Identification of Rock Types in an Arid Environment by Air Photo Patterns.* U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, ETL–0261, AD–A102 893.

Ehlen, J. 1983. *Evaluation of Criteria for Identifying Metamorphic Rocks on Air Photos: Two Case Studies in the Northeastern United States.* U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, ETL-0326.

Frost, R.E.; Johnstone, J.G.; Mintzer, O.W.; Parvis, M.; Montano, P.; Miles, R.D.; and Shepard, J.R. 1953. *A Manual on the Airphoto Interpretation of Soils and Rocks for Engineering Purposes.* Purdue University School of Engineering, Lafayette, IN.

Helenek, H.L. and Mose, D. 1976. "Structure, Petrology and Geochronology of the Precambrian Rocks in the Central Hudson Highlands." *IN* Johnson, J.H. (ed), *Guidebook to Field Excursions,* 48th Annual Meeting of the New York State Geological Association, pp. B-1-1 to B-1-27.

Ratcliffe, N.M. and Helenek, H.L. "Bedrock Geology of the Peekskill Quadrangle, New York." *U.S. Geological Survey Bulletin* (in preparation).

Rinker, J.N. and Frost, R.E. 1981. "Remote Sensing for Engineering Site Selection." *Proceedings of the International Conference on Computing in Civil Engineering,* American Society of Civil Engineers, pp. 359-371.

Rinker, J.N. and Corl, P.A. 1983. *Air Photo Analysis and Feature Extraction.* U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia. Report in progress.

Schiffman, P. and Liou, J.G. 1980. "Synthesis and Stability Relations of Mg-Al Pumpelleyite, $Ca_4Al_5MgSi_6O_{21}(OH)_7$." *Journal of Petrology*, vol. 21, pp. 441-474.

Way, D.S. 1973. *Terrain Analysis, A Guide to Site Selection Using Aerial Photographic Interpretation,* 2nd edition. New York, McGraw-Hill Book Co.

Winkler, H.G.F. 1979. *Petrology of Metamorphic Rocks,* 5th edition. Springer-Verlag New York, Inc.

Zen, E--an. 1961. "Stratigraphy and Structure at the North End of the Taconic Range in West-Central Vermont. *Geological Society of America Bulletin,* vol. 72, pp. 293-338.

Zen, E-an and Hartshorn, J.H. 1966. *Geologic Map of the Bashbish Falls Quadrangle, Massachusetts, Connecticut, and New York.* U.S. Geological Survey GQ-507.

Zen, E-an and Ratcliffe, N.M. 1971. "Bedrock Geologic Map of the Egremont Quadrangle and Adjacent Areas, Berkshire County, Massachusetts and Columbia County, New York." U.S. Geological Survey Miscellaneous Geologic Investigations, Map I-628.

APPENDIX A. Pattern Element Descriptions for the Massachusetts Area Mapping Units.

UNIT	LANDFORM	DRAINAGE: PLAN	DRAINAGE: CROSS SECTION AND GRADIENT	PHOTO TONE	PHOTO TEXTURE
1	A fairly steep slope on the extreme edge of the photo	Parallel Extremely sparse Very low density	Woods obscure cross section Steep gradient	Wooded: n/a	Wooded: n/a
2	Low-lying, gently rolling aprons around bases of hills Gently rolling, some elongate hills Generally cleared and cultivated Looks karsty in places; small pits that look natural Several manmade pits Some outcrop in west, between hills and floodplain Slopes gentle Relief low	Pseudo-radial pattern; individual streams dendritic with some structural control A few third-order tributaries, but mainly second-order -- little branching and the few branches of moderate length Moderate density	Saucer-shaped cross sections on tributaries; U-shaped larger streams Very low gradients	Light to medium gray, slightly mottled Outcrop light	Generally fine and smooth, but occasionally rough
3	Broad, NNW- trending, ridge with broad, flattish crest Slightly asymmetrical, steeper slope on NE side Large rounded knobs on crest One very steep flatiron at extreme SE corner Slopes moderate Relief moderate to high; within ridge itself, fairly gentle	Dendritic Third-order tributaries Very widely spaced; low density Main streams and second-order tributaries very long and straight; third-order tributaries also straight, but about 1/3 the length of the second-order tributaries	Woods obscure cross section: one large stream with deep, slightly open V--shaped cross section	Wooded: n/a	Wooded: n/a

APPENDIX A. Pattern Element Descriptions for the Massachusetts Area Mapping Units. (Continued)

UNIT	LANDFORM	DRAINAGE: PLAN	DRAINAGE: CROSS SECTION AND GRADIENT	PHOTO TONE	PHOTO TEXTURE
4	Long, narrow, steep-sided asymmetrical NNW-trending ridge Narrow, relatively sharp, slightly sinuous crests Slopes smooth, even, and consistent High relief Dip to WSW Some outcrop visible along crest; may overhang slope in SE corner	Parallel/pseudo-radial No tributaries Low to moderate density: low on NE-facing slope, moderate on SW-slope Tributaries and main streams in other units parallel NE border	Woods obscure cross section Moderate to steep gradient	Wooded: n/a Outcrop light	Wooded: n/a Outcrop rounded
5	Narrow band trending NNW Looks like a step or terrace, but not streamlined or smooth; tree heights are uneven, suggesting unevenness in terrain Low elevation, flattish topped Slopes gentle to moderate Relief low	Trellis-type First- and second-order tributaries only: no branching; first-order, quite long; second-order, moderate Very low density	Woods obscure cross section Moderate gradients in ENE; gentle in NNW	Wooded: n/a	Wooded: n/a
6	Too small an area to evaluate				
7	Low elevation, broad, flat to gently sloping areas on the south side of main stream; separated from adjacent landforms by distinct breaks in slope Slopes inward toward stream Some small, light-toned pits (7a) which may or may not be manmade Agricultural	Very little drainage; what there is, dendritic Second-order tributaries; some branching Low to medium density Streams curved to slightly wiggly	Gradients, low Cross sections, shallow and indistinct	Dull, medium gray with some mottling	Fine, smooth

APPENDIX A. Pattern Element Descriptions for the Massachusetts Area Mapping Units. (Continued)

UNIT	LANDFORM	DRAINAGE		PHOTO TONE	PHOTO TEXTURE
		PLAN	CROSS SECTION AND GRADIENT		
8	Flat area bordering main stream: floodplain Agricultural	Dendritic Main stream wiggly, as are some tributaries Second- and third-order tributaries common; some branching Third-order tributaries very short and barb-like Medium density	Cross sections, obscured by vegetation; or very shallow and indistinct Gradients very low	Dull medium gray	Fine, smooth, even

END

FILMED

12-83

DTIC